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# Radiography and Corrosion Analysis of Sub-merged Friction Stir Welding of AA6061-T6 alloy

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**Abstract**

Friction Stir Welding (FSW) is considered to be the most significant development in metal joining in recent decades. In this investigation, the quality and corrosion behavior of a submerged friction stir welded sample of AA 6061-T6 alloy were studied. This paper examines the three parameters used for this process such as rotational speed (rpm), welding speed (mm/min) and water level (mm). Visual inspection, X-ray radiography, micro-structural evolution and corrosion testing were employed to analyze the welded samples. A total of three levels (low, medium and high) were used for rotational speed (rpm) and welding speed (mm/min), each along with three varying water levels (mm) for radiography and corrosion analysis of the nine samples. No defects were observed on the weld region via visual inspection. Radiography tests indicate various defects in the welded samples with higher water level as its parameter. The interfacial and nugget region of the welded sample was also studied for the defect free sample evaluated by radiography technique, using Scanning Electron Microscope (SEM), showing no defects, good mixing and re-crystallized structure. The corrosion rates of the welded samples were studied via polarization in 3.5% Na-Cl solution, showing a high corrosion rate for samples with higher water level as their parameter.


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*Keywords:* Friction Stir Welding; Sub-merged Friction Stir Welding; Radiography and Corrosion analysis

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## 1. Introduction

Friction stir welding (FSW), a new solid-state joining technique, was invented by The Welding Institute (TWI) of UK [1]. This technique avoids the formation of solidification cracking and porosity. Moreover, this joining technique is energy efficient, environment friendly, and versatile. It can be used to join high strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding. In FSW, a non-consumable rotating tool with a special geometry, consisting of a pin and a shoulder sweeps the weld seam, and joins the work pieces while traversing along the seam. Major process parameters such as rotational speed and feed rate, influence the quality of the welds. These parameters are responsible for generating the frictional heat and creating the stirring mechanism that joins the materials effectively [2, 3]. In recent years, the particular interest is to improve the joint properties by controlling the temperature level. For this, the whole work piece is immersed in the liquid during the welding which is called Submerged Friction Stir Welding (SFSW) [4, 5]. Tokisue et al [6] were the first to use submersion in a friction joining process.

Non-Destructive Tests (NDT) are a wide group of analytic techniques used in science and industry to evaluate the characteristics of a material or component without causing damage to it. The techniques used are non-invasive. Lie et al [7] have reported on multiple non-destructive testing methods on the FSW of AA 2219-T6. Many different types of NDT methods exist, the most commonly used ones being ultrasonic testing, magnetic particle testing, liquid penetrant inspection, radiographic testing and eddy current testing. Finally, they have concluded that each of the non-destructive tests has its limit. Esther T.Akinlabi et al [8] stated that non-destructive testing techniques, viz, visual inspection and radiography were successfully conducted on dissimilar friction stir welds between 5754 aluminum alloy and C1100 under various parameter conditions. They have concluded that the visual inspection is not the best technique for detecting the defects in the welded sample; the x-ray radiographic testing technique successfully detected the defects in the welded sample. L.S.Rosado et al [9] used eddy current's probe to detect the imperfections in the friction stir welding of metals.

Corrosion is defined as the destruction or deterioration of a material because of its reaction with environment. Pitting is one of the most destructive and insidious forms of corrosion. It causes the equipment to fail, because of perforation with only a small percent weight loss of the entire structure. From a practical standpoint; most pitting failures are caused by chloride and chlorine containing ions [10]. Omar Hatamleh et al [11] have investigated of effects of surface treatment techniques like laser and shot peening on the stress corrosion cracking (SCC) susceptibility of friction stir welded (FSW) 7075 aluminum alloy joints. None of the peening techniques resulted in an improvement of the tensile properties of the welded sample of aluminum alloy. The pits size and number were large on the unpeened surfaces and the shot peened surface also had fewer pits than the unpeened surface. T.Udayakumar et al [12] have found the corrosion current decreasing with an increase in the friction force, which reaches a minimum and then increases. In the case of the upset force and burn off length, the corrosion current seems to decrease reaching a minimum, and then increases. D.A.Wadeson et al [13] described the corrosion behaviour of FSW aluminum alloys. Generally, it has been found that the weld zones have a faster corrosion rate than the parent metal. G. Elatharasan et al [14] have investigated the corrosion properties of friction stir welded 7075-T6 aluminum alloy plate by polarization, and electrochemical impedance spectroscopy in 3.5% Na-Cl. They found that the root side of the weld exhibited higher susceptibility to inter-granular corrosion.

In this investigation, a total of three levels (Low, Medium and High) have been used for rotational speed and welding speed, each with three levels varying water levels for radiography and corrosion analysis. The radiography tests provide us adequate information about the quality of the submerged friction stir welded pieces. The corrosion test was performed to study the corrosion rate of the submerged friction stir welded pieces. Such work has not been conducted until now.

## 2. Experimental setup

For the experimental of SFSW on AA 6061-T6, the material selected for the fixture used, was mild steel (0.3 % C). AKRYLIK (Plexi-Glass) was chosen as the material of the tank. This material has been chosen for the sole purpose of the vicinity of the friction stir welding. This material also aids in the direct measure of the level of the water used in the tank. Fig.1. shows the experimental setup of underwater FSW.


Fig. 1. Submerged friction stir welding experimental set-up

The base metal (BM) AA6061-T6 alloy used for the experiment is 100 mm x 70 mm x 6 mm. The chemical compositions (mass fraction, %) of the BM are Cr-0.003, Cu-0.010, Mn-0.061, Fe-0.156, Mg-0.43, Ti-0.008, V-0.08, Zn-0.01, Si-0.516 and Al balance. The fixture was fixed inside the tank by bolting it to the table, and the various samples were clamped on it. Water was poured at room temperature into the tank, so that the top surface of the samples was immersed in it. The water level was chosen by taking into account the thickness of the gasket sheet and fixture (~30mm), and it was gradually increased by 15mm of head. Fig. 2 shows a processing view of friction stir welding under the water. The volume of the water in relation to the water level for the first process parameter, amounts to 2.7 liters. Similarly, it is increased for various parameters as shown in Table 1.

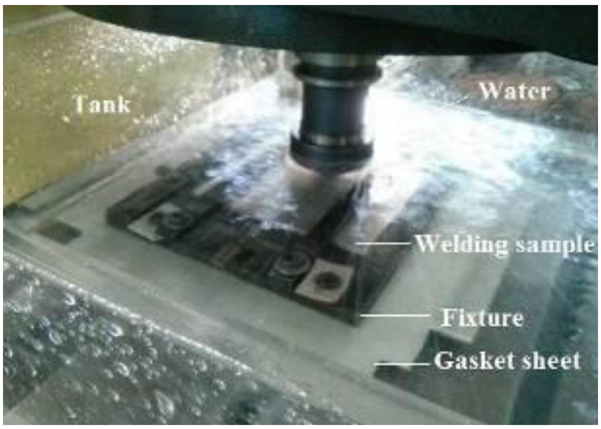



Fig. 2. Processing View of SFSW

Table 1. Welding parameters used to perform the SFSW process

| S.No. | Parameter | Symbol | Low | Medium | High |
|---|---|---|---|---|---|
| 1. | Rotational Speed (rpm) | (ω) | 800 | 1000 | 1200 |
| 2. | Welding Speed (mm/min) | (v) | 30 | 45 | 60 |
| 3. | Water level (mm) | (h) | 45 | 60 | 75 |

A non- consumable tool was used throughout the whole experiment, made of tool steel. The dimensions were shoulder with a diameter of 15 mm, and pin which is 6 mm in diameter and 5 mm in length, as shown in Fig. 3.

Fig. 3. SFSW tool

An axial load of 14kN was maintained constant. The SFSW weld is performed approximately to 100 mm in length. Iridium 192 source is used in the radiography equipment. The distance between the X-ray emitter and weld sample was maintained as 1 m. The expose time of 30 min and resonance signal of 740 mR/hour were maintained. The submerged welded plates have been analyzed using Optical Microscopy (OM). Polished samples were etched with Keller's reagent (a mixture of 2.5 ml nitric acid, 1.5 ml hydrochloric acid, 1 ml hydrofluoric acid and 95 ml water) for 20 s [15].The corrosion rate of friction stir welded AA6061-T6 alloy plate has been investigated by the potentiostatic corrosion testing equipment, as shown in Fig.4. The SFSW samples of 1 cm x 1 cm dimension were cut from the plate. 3.5% sodium chloride was used in this study.

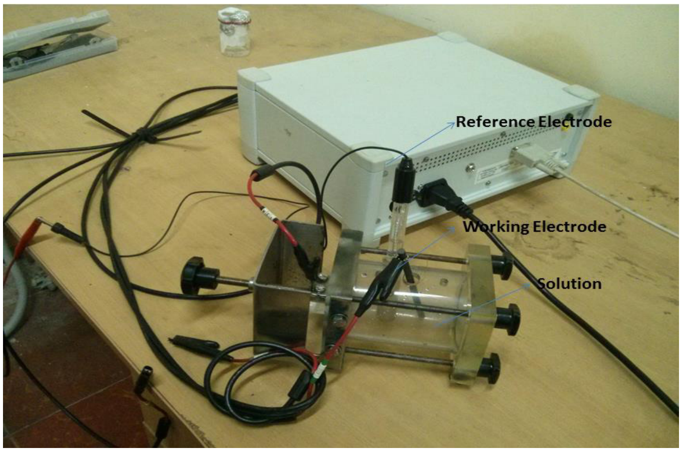



Fig.4 Corrosion testing equipment

## 3. Results and discussions

### 3.1. Visual inspection of the welds

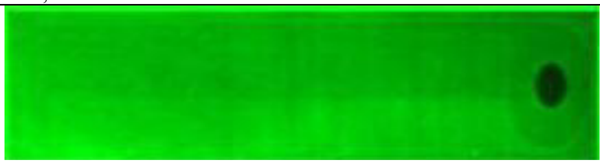
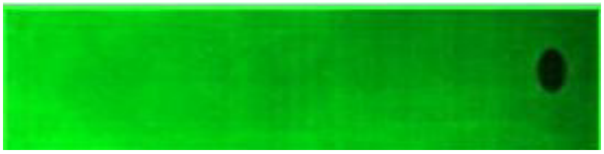
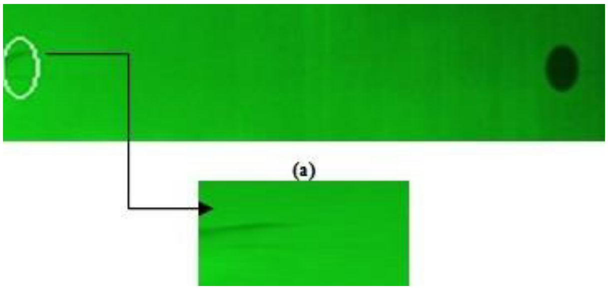
Typical welds produced at 1200 rpm, 45 mm/min and water level 75 mm are presented in Fig. 5. Due to the nature of the surface appearances of the submerged friction stir welded samples, it was difficult to observe any surface defects. No significant cracks, voids, wormholes or other surface deformities were observed in any of the weld samples produced.

Fig.5. SFSW pieces of combination of 1200 rpm, 45 mm/min at a water level of 75 mm

### *3.2. Radiography test of the welds*

The results of the radiographic tests conducted on the welds produced at 800 rpm, 30 mm/min and various water levels of 45, 60 & 75 mm are shown in Table 2. The results show that a crack defect was noticed at water level 75 mm.

Table 2. Radiograph of welds 800 rpm, 30 mm/min and water level 45, 60 & 75 mm

| Radiography Image for 800 rpm,30 mm/min and different water levels at 45,60 & 75 mm | Remarks |
|---|---|
|  | No evidence of wormholes, voids and cracks. |
|  | No defects. |
|  (a) (b) | Cracks formed in the weld region during the welding process. |

The results of the radiographic tests conducted on all the welds produced at 1000 rpm, 45mm/min, and different water levels at 45, 60 & 75 mm, are shown in Table 3. With reference to Table 3, a void defect was found at the joint interface at high water level. The results of the radiographic tests conducted on all the welds produced at 1200 rpm, 60 mm/min and different water levels of 45, 60 & 75 mm are presented in table 4. With reference to table 4, worm holes defects were found at water level 75 respectively. In Table 2, Table 3 and Table 4, (a) and (b) show defects over the weld region, and enhanced view of the defects respectively. Internal cracks, voids and wormhole defects were identified at water level 75 mm from the radiographic test. It was observed that, more bubbles were developed towards the welding direction when underwater friction stir welding was performed at higher water level. This may lead to defects in the weld region due to lesser degree of fusion.

Table 3. Radiograph of welds 1000 rpm, 45 mm/min and water level 45, 60 & 75 mm

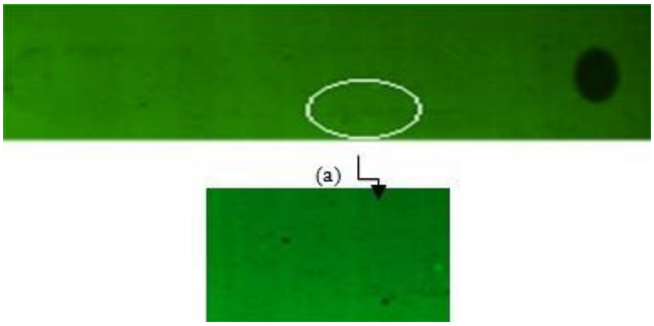
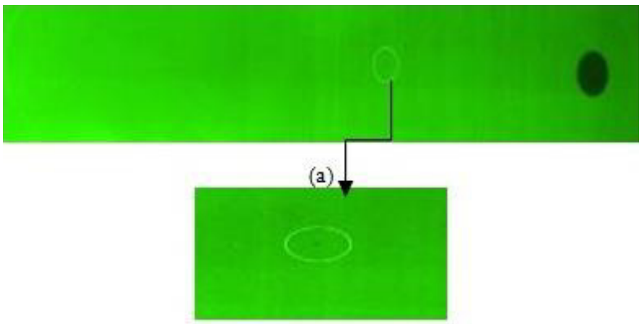
| Radiography Image for 1000 rpm,45 mm/min and different water levels at 45,60 & 75 mm | Remarks |
|---|---|
|  | Complete penetration. No defects. |
|  | Defects free weld. |
|  (b) | Voids defect is depicted. |

Table 4. Radiograph of welds 1200 rpm, 60 mm/min and water level 45, 60 & 75 mm

| Radiography Image for 1200 rpm,60 mm/min and different water levels at 45,60 & 75 mm | Remarks |
|---|---|
|  | Defects free weld. |
|  | Defects free weld. |
|  (b) | Worm-holes defects over the weld region. |

## *3.3. Micro-structural evaluation*

The micro-structural analysis aids the radiography test for further confirmation that the welded sample is detect-free. Fig. 6 (a-c) shows the microstructure of the submerged friction stir welded sample at low rotational speed, low welding speed and medium water levels such as 800 rpm, 30 mm/min & 60 mm. Fig. 6(a) shows the microstructure of the parent metal with coarse grains.Fig.6(b) and (c) show the interfacial and nugget regions of the welded sample. It was observed that the interfacial regions of the welds had no defects, and the nugget region had a re-crystallized structure.

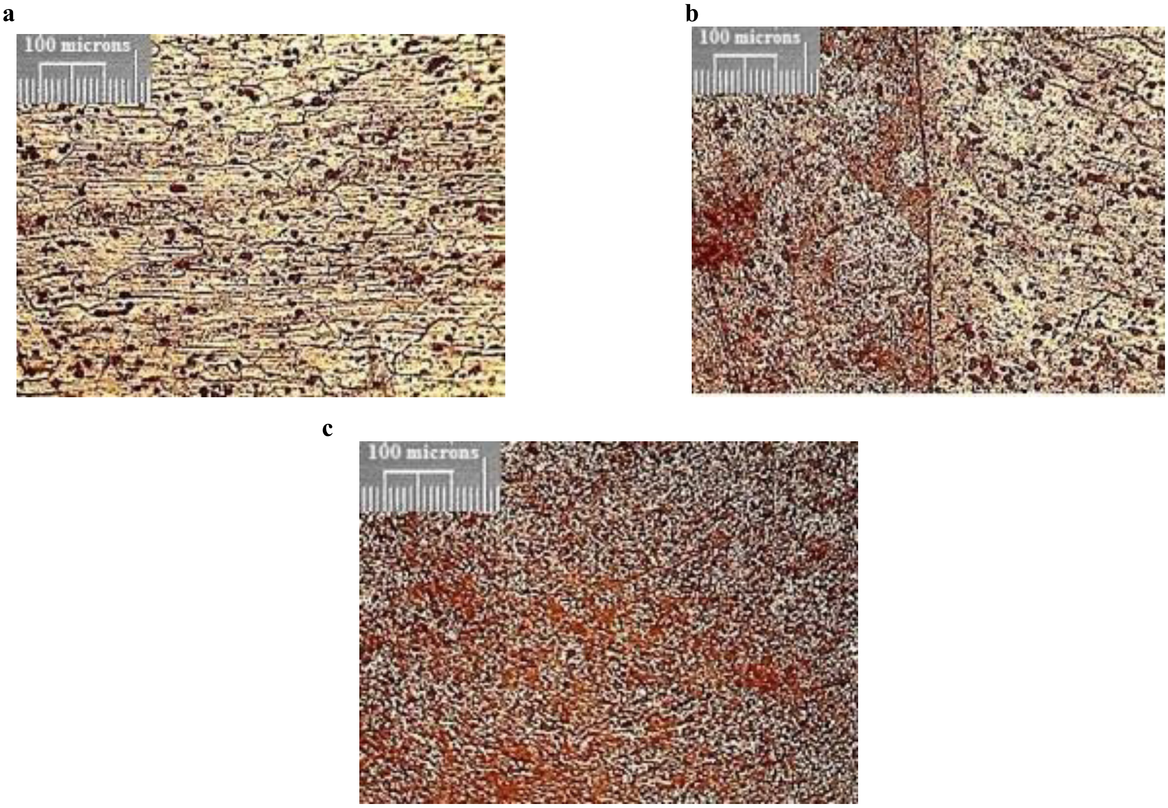



Fig.6. Microstructure of the submerged friction stir welded sample at 800 rpm, 30 mm/min and 60 mm (a) parent metal; (b) interfacial regions; (c) nugget zone

## *3.4. Corrosion analysis of the welds*

Tafel polarization tests were carried out to find the pitting corrosion rate of the submerged friction stir welded sample. The anodic polarization curves shown in Fig. 7, were obtained by exposing the welded area alone to 3.5% NaCl solution for 1200 rpm, 60 mm/min and water level 45 mm parameter conditions. This technique shows the rate of the current in relation to the potential applied for the necessary control of the rate of corrosion. Similarly, the corrosion rate of the weld samples for all parameter conditions was tabulated from the anodic polarization curves, and is shown in Table 5. From the table, the maximum corrosion rate has been obtained in the case where the water level is high.

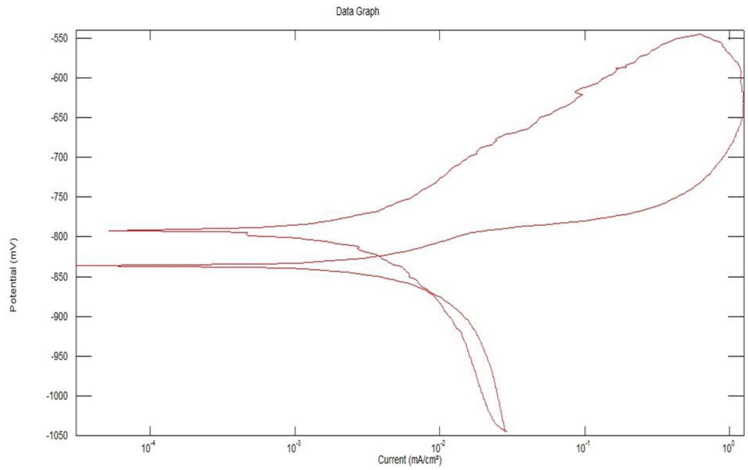



Fig. 7.Polarization curves of SFSW of AA6061-T6 alloy at 1200 rpm, 60 mm/min and water level 45 mm conditions

Table 5. Corrosion rate (mm/year) of SFSW of AA6061-T6 alloy

| S No. | Rotational speed(rpm) | Feed rate (mm/min) | Water level (mm) | Corrosion rate (mm/year) |
|---|---|---|---|---|
| 1. | 800 | 30 | 45 | 2.98 |
| | | | 60 | 3.15 |
| | | | 75 | 4.63 |
| 2. | 1000 | 45 | 45 | 2.14 |
| | | | 60 | 2.86 |
| | | | 75 | 3.01 |
| 3. | 1200 | 60 | 45 | 1.75 |
| | | | 60 | 2.05 |
| | | | 75 | 2.25 |

## 4. Conclusions

The following conclusions are made from the experimental study of submerged friction stir weld of AA6061-T6 alloy.

- Visual inspection, radiography and corrosion tests were successfully conducted on the welds of 6061-T6 aluminum alloy. Defect free welds were observed from the visual inspection for all the selected parameters.
- Crack defects were found at 800 rpm, 30 mm/min and water levels 75, Void defects were noticed at 1000 rpm, 45 mm/min and water level 75 mm, and wormholes were identified at 1200 rpm, 60 mm/min and water level 75 mm from the radiography testing technique. However, the visual inspection failed to prove this.
- The defect free samples were identified radiography technique, and the microstructure using Scanning Electron Microscope (SEM) revealed good fusion and re-crystallized structure.
- A high corrosion rate 4.63 mm/year has been obtained at 800 rpm, 30 mm/min and water level 75 mm.

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